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RADARS IN SPACE

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I will discuss some of the capabilities of active microwave devices operating from space (typically, radar, scatterometers, interferometers, and altimeters, fig. 1). Figure 2 gives a brief outline of items to be covered in this discussion. General radar parameters and some basic radar principles are explained first, applications of these parameters and principles are explained next, and, finally, trends in space radar technology and where space radars and active microwave sensors in orbit are going are discussed. With any of these active microwave devices, you can control certain things, and I have listed those items in figure 3. These aspects include frequency, modulation, polarization, incidence angle, pulse repetition frequency, and pulse width. There are other aspects that you might be able to control on your own instrument, but if you are riding "piggyback" on somebody else's satellite, you can't control the orbit or the satellite's position. The best thing to do in a case like that is to record the position of the satellite so that you can back out your own data later on. Then you are in a good position to determine sigma-naught (σ^0), which is a measure of the facet scattering of the reflecting surface. The σ^0 quantity can be determined for your chosen or observed conditions, and, once you get that number as a function of whatever conditions you have, then you can try to relate that to conditions you are interested in.

An example of surface scattering is shown in figure 4. Look at the top row. If you have a really flat smooth surface, then you have a reflection whereby the angle of reflection is equal to the angle of incidence, shown in the figure as θ. But notice what happens if the surface gets a little rough. The rougher the surface becomes, the greater the likelihood you will have energy reflected in different directions. Where the surface becomes really rough, there is energy reflected in all directions. You can only hope that some energy comes back toward the source direction, so that you can make a measurement.

Let's now define this σ^0 quantity. Imagine there is a ray of energy coming toward you. Now, σ^0 is simply the measure of the energy scattered in the direction that you are interested in. Usually it's the direction that the incidence wave is coming from. σ^0 for any surface may vary with incidence angle, azimuth, frequency, and polarization. The rougher the surface, the more likely it is to get isotropic scatter (scatter in many directions). If I draw a dashed line around the amount of reflected energy to represent isotropic scatter, then σ^0 is defined as 1, or 0 dB. Other values of σ^0 would be represented by longer or shorter arrows (as shown in fig. 4). Shorter arrows would be a σ^0 of less than 1, or negative dB if you work in log space. Likewise, if you have more energy scattered in the direction you are interested in, then you have a σ^0 of greater than 1 in ratio space, or positive decibels. σ^0 values of terrestrial features as measured from space span a very wide range, and the measured value depends on the roughness and is much lower for flatter surfaces and higher for rougher surfaces.

The sampling scheme also can affect your measurement. There is a problem defining σ^0 for point sources. Figure 4 shows distributed targets. There are two common models for scattering. One of them is the specular, or optical, model and the other is the Bragg, or point scatterer model. Specular scattering is similar to what happens at the sides of a billiard table. Each reflecting surface is called a facet.

So, for example, if the incident energy is from a certain direction, and there is a facet tilted back toward the source, you get a lot of reflected power. Other facets, however, don't get very much power back. So specular scattering is good for near-nadir calculations.

The Bragg, or point scatterer, model has a surface that is represented as a summation of sinusoidal surfaces, each one with its own characteristic wavelength. In Bragg scattering, the surface component which has a wavelength approximately twice the size of the radar wavelength will be sifted out, or selected. That surface component is the one from which you get the most reflection. This concept was used extensively for the SEASAT wind-measuring scatterometer where the wavelength was approximately 2 cm. Even from orbit this 2-cm radar wavelength was very sensitive to the 1-cm capillary waves, the little "cat's paws" on the water surface, not to the general tilt of the ocean. Here the σ^0 in Bragg scattering is proportional to the energy spectrum of the little wind-induced ripples; that is how the wind measurement is made.

The upper graph of figure 5 represents both specular and Bragg scattering efficiencies as a function of incidence angle off of nadir. Notice the pronounced fall-off with incidence angle for the specular model. On the other hand, the Bragg scattering is flatter. What happens in the real world, of course, is a summation of those two as you move from nadir out to grazing. In the lower graph of figure 5, notice that as the surface gets rougher, the angular dependence decreases. If you have a very smooth surface and you try to measure σ^0 as a function of incidence angle, then you'll see that the amount of signal you get back is very sharply dependent on incidence angle. On the other hand, if the surface is very rough, then the amount of signal that returns is not going to be very dependent upon incidence angle. You can test this idea yourself if you're on the side of a lake in the evening, with a point source of light on the opposite shore. If the water is very calm, then any reflection you see on the surface of the water is going to be very angle-dependent; that is, the reflection occurs at only one spot on the lake surface. But, if the water gets rougher, then that single point source of light is reflected from a patch of water surface representing a spread of incidence angles.

Let us now discuss volume scattering. You get internal reflections (fig. 6) beneath the first surface, and energy gets scattered around inside. Some of this energy comes back toward you. Penetration depth is associated with this energy, and this penetration depth, like all good penetration depths, is the depth at which the intensity is e^{-1} of what it was at the surface. The penetration depth is given by this expression, where the ϵ's are simply the dielectric constants of the layered media traveling from one stratum down to the next. What we need to know about this expression is that at typical microwave wavelengths for dry soils, you might get approximately 1 meter penetration; for very dry sands in deserts, tens of meters; and for polar ice sheets, hundreds of meters. This allows all kinds of opportunities for looking at subsurface entities.

Now, we will review antenna patterns. Figure 7 is a representation of a beam with two side lobes. Beam width, β, is given by this expression where the beam width is approximately equal to the wavelength divided by some dimension of the antenna. This is an approximation to a numerical solution; it comes from a transcendental equation. The term λ is the wavelength involved, and there is a width and length for the antenna, unless it is circular; then, of course, you have a diameter. Width and length are being used here as two dimensions from a two-dimensional antenna. The antenna pattern that you generate from some test equipment might look something like the lower left part of the figure, where the side lobes are represented as little bumps. If the power at the peak, or center, is 0 dB, then 3 dB down is the half-power point. The beam width is defined as the angle between the two half-power points.

The radar equation is shown in figure 8. An antenna at altitude h, using wavelength λ, sends out a pulse, and a reflection then appears. P_i is just the power intensity incident on a scattering surface that measures X_a long by X_r wide. P_i equals the transmitted power multiplied by the antenna efficiency. There is an angular dependence and the inverse square law for the spreading of energy. P_c is returned power intensity back at the antenna (now acting as an energy collector for the receiver). If we multiply P_c by the dimensions W and L, then we get the amount of power that is incident on the antenna. P_r is the amount of power received, which is just P_c times the area of the antenna. So this (P_r) is the expression we want; this is really one form of the radar equation. The power received is P_r, but basically the expression includes the following: the transmitted power P_t (which you can control), the size of the antenna, the speed of light, σ^0, a few trigonometric functions, β (the beam width), the altitude of the orbit (distance above the ground), and the radar wavelength. Associated with this radar equation must be a signal-to-noise ratio (SNR), which is the power received, divided by the thermal noise in the antenna. Here, k is the Stefan-Boltzman constant, T is absolute temperature, and BW is bandwidth. You know many of these things, you have to keep track of others, and you measure P_r back at the antenna. Then you back out σ^0 and model it to whatever you are interested in (such as rain rate or surface roughness).

Figure 9 shows the formation of a resolution cell on the ground. For a sideways-looking sensor, we use two dimensions on the ground; one is azimuth and the other is range. Azimuth is the direction the spacecraft is moving, and range is crosstrack to that direction. We will use azimuth and range as our two ground dimensions. Imagine a spacecraft moving along in perspective view with the subtrack of the satellite on the ground underneath it. The beam is alongside looking in the crosstrack direction. (This is just for explanation purposes, because it eliminates the Doppler.) We will discuss Doppler later on; however, right now there's no radial component of velocity between the target area and the orbiting radar; therefore, there is no Doppler shift in the returned signal.

I want to explain how we get the cell size and shape on the ground based on the different radar and orbit parameters. These pulses radiating out along the beam are adjacent wavefronts. They can be as close together as $\frac{c\tau}{2}$. τ is the pulse width, which is equal to one over the bandwidth. You can set up a train of these pulses, but if you get them any closer together than the pulse width itself you really don't have a pulse train anymore. I assume that you would always want to get the finest resolution on the ground that you possibly could so this would be the minimum spacing in the range direction. If you project that onto the ground, the resolution in the range direction comes out to be, with the appropriate geometry, typically 20 m for microwave frequencies and bandwidths. Therefore, you have approximately 20 m in the range direction, which is pretty good. On the other hand, if you do the same calculations for the azimuth direction, you get an expression that gives typically 1 to 2 kilometers, which is not very good. If you are not trying to image some discrete object or shape, then 1 to 2 km might be acceptable. Notice one thing: the range resolution does not have an h in it. The term h, you may remember, is the altitude of the spacecraft. We have these two expressions, X_r for the resolution in range and X_a for resolution in azimuth. They are approximately 20 m and 1 or 2 km, respectively.

Let's now review ways to improve the ground resolution. Figure 10 illustrates how to do it. At the top of the figure is the expression that existed before for Δ_r, the change in range distance from 1 resolution cell to the next. In other words, this is the finest resolution you can see on the ground. This expression represents the speed of light divided by the bandwidth or the speed of light times the pulse width. To make Δ_r smaller, there is a constraint. The transmitted energy is equal to peak power multiplied by the pulse width. If the pulse width is too small, then there might not be enough energy in the returned pulse to be detected. There must be a reasonably sized pulse width. One solution is to try different methods of modulation, such as chirping, phase modulation, and various other techniques to improve that range resolution. Most scientists think 10 to 20 m is very useful for most geophysical studies.

Consider how to improve the azimuth resolution. In figure 10, you see that the minimum detectable spacing between adjacent things in the azimuth direction on the ground goes is the altitude times the radar wavelength divided by the size of the antenna. The obvious thing is to do something about either λ (the wavelength) or L (the size of the antenna). If you try to make λ smaller (in regard to microwave) and λ is already pretty small, you can go into millimeter-wavelength radar. The other possibility is to do something about L, the size of the antenna. We will explain this further when we discuss synthetic aperture radar later in this paper.

First, we will discuss Doppler processing. In figure 11, we swing the same radar beam forward. Again suppose that the spacecraft is moving along with the same geometry as we discussed before, only now, instead of this radar beam pointing straight out crosstrack, it's aimed somewhat forward. This was the arrangement used in the SEASAT scatterometer and various proposed scatterometers yet to be flown. On the left of figure 11 is a perspective view, and on the right is a plan view, both of the same thing. Notice the lines of equal Doppler shifts and the lines of equal range on the ground. Now let's consider one area in which we are interested. Look at the bottom portion of figure 11; we can see how we actually form this cell. The lines of equal Doppler are present because of the radar receiver's filter, specified by a Doppler filter response curve with a width equal to the noise bandwidth. There will be other similar ones laid out at different Doppler shifts. When you want to look at objects on the ground that lie between adjacent Doppler lines ("isodops"), you tune them in with the appropriate Doppler filter. Likewise, with time delays you are looking at ground or water between two adjacent range rings, and range is really equivalent to time. A third way to select what you want is to aim the antenna. The half power points might lie at the nulls on either side of the peak, seen also as bold lines at the bottom of figure 11, from the upper right drawing. Also consider that while all of this is happening, the spacecraft has progressed along its orbit so that this cell (which is the instantaneous field of view) becomes smeared. The result of the smeared cell is an irregular hexagonal shape, which is just one cell. There are other cells along the beam, and there might even be other beams. That is how we get Doppler cells on the ground for a real aperture radar.

The antenna beam arrangement for SEASAT's scatterometer was as shown in figure 11, with four beams spaced 90° apart. Each spot on the ocean was sampled twice. First, the forward beam on one side would hit a patch of water, and then the aft beam on the same side would hit it. Therefore, you got two different azimuthal looks at the same patch of water. It turned out that the model function between σ^0 and the geophysically interesting parameters (namely, wind speed, in this case) can give both wind speed and wind direction. Remember, it is the wind that sets up the capillary waves on the water, and that is what the scatterometer was looking at. It was using a 2-cm wavelength, which is related by Bragg scattering to the 1-cm capillary ripples on the water. The model function states that if you have at least two different azimuth looks, you can determine both wind speed and wind direction. It was highly successful even though there were only 3 months of data. Scientists are still analyzing that data 11 years later. Charts of the global distribution of wind vector have been published. Some of them have been on the covers of *Science* and *Aviation Week*. The radar gives you multiple looks at the same patch of water. With a second look, you get wind speed and an ambiguous direction, but the ambiguity is usually 180°, and you have other information that helps you eliminate the ambiguity. The proposal for the next scatterometer after SEASAT, which would have been the Navy Remote Ocean Sensing System (NROSS), was cancelled in 1980. This scatterometer would have had the same four beams, along with a science beam out front, which would have guaranteed that each patch of water that lay along the satellite's subtrack would be hit at all different incidence angles, so that a lot could have been learned concerning dependence on incidence angle.

Now let us consider synthetic aperture radars (SAR's). SAR's enable you to get extraordinarily fine resolution in the azimuth direction with an orbiting radar or even with an aircraft radar. The premise is that in a certain amount of time the beam width of the antenna is repeated along the ground, as shown at the top of figure 12. You can control the overlapping or gapping by regulating the duty cycle of the transmitter. If you set the overlapped distance to 0, then you move a distance in orbit that gives you a distance on the ground such that there is no overlap and there are no gaps. On the other hand, if you deliberately allow overlap, then you get multiple samplings of each small area on the ground. This turns out to be very useful for imaging radars. The real beam width (β) is equal to the wavelength divided by the linear dimension of the antenna. As you can see in the top portion of figure 12, you can get an expression for this script L, which is a synthesized antenna length. Now you can calculate a synthetic beam width (β_S), which is equal to λ divided by this script L instead of the normal L. As the antenna moves along its path in orbit, data must be recorded and the antenna has to be stabilized. The script L becomes the effective dimension of the antenna. If we combine the equations shown in figure 12, then we find that the x_a in the azimuth direction equals half the size of the real antenna, which is really exciting. Now we have an expression that shows that the resolution on the ground in the azimuth direction is down to a few meters. We have both the x_a and x_r down to a few meters. That is the basis of synthetic aperture radar, which affords us all kinds of opportunities for very fine resolution on the ground, in <u>both</u> dimensions!

In figure 13, we describe radar altimeters, which are technically radars. You send out a pulse, and you listen for the echo; it is an active microwave device. Imagine that a pulse is formed and sent to the ground, or to the ocean surface, and you listen for the return. This is just a simple radar or radio altimeter such as those that exist on an airliner or a military aircraft. Altitude is what you want to measure precisely, and it is simply the speed of light or the speed of electromagnetic waves multiplied by the time interval. Actually, you use the time between when you sent the pulse and when you heard the return, divided by two, because it is a complete trip. This measurement is accurate to delta h, which is c times the pulse width divided by 2, which is also c over twice the bandwidth. There are two ways to use radar altimeters. One way is the beam-limited method (shown here in the center); this is used for terrain that varies a lot on the ground. The other way is the pulse-limited method (shown here on the right); this is used for relatively smooth surfaces like the ocean. The question is, then: why don't you use it as beam limited all the time, and not as pulse limited, so that you will always get better resolution on the ground? The reason is, of course, that the beam width is related to the antenna size. Beam-limited requires a longer antenna than pulse-limited, and so if you want to use a smaller antenna and cut down your cost and your stability problems, you need to use pulse-limited. Beam limited is more useful, but pulse limited is cheaper to build and operate.

The altimeter used on SEASAT, flown in 1978, was a simple instrument with which a tremendous amount was learned. That particular instrument was optimized for ocean studies. What was learned about ocean dynamics was substantial because now we have accuracies down in the 50-centimeter range. We can now obtain data for testing all these theories about dynamic heights across the Gulf Stream, where there are just a few meters change in sea surface height across several hundred kilometers.

I've listed in figure 14 some geophysically interesting targets for active microwave; however, this list will never be complete. The SEASAT scatterometer dealt primarily with wind vector over the ocean. Other targets for active microwave are both the extent of ice (whether it's there or not) and the classification of ice into first year or multi-year. In regard to vegetation and snow (the extent and the wetness of the snow), it turns out that microwave radars are very sensitive to the wetness of the snow. These instruments are really good at discerning dry snow from wet snow.

Let's mention some of the advantages of active microwave. Since the target area need not be sunlit, radar is a day-night system. Microwave is also an all-weather (within certain limits) system, since it can, in many circumstances, penetrate clouds. By this statement I mean that if the rain cells are really heavy, then, of course, you have detected rain. But you can't really look through those rain cells; that is why a combined active/passive approach is useful. Another big advantage of active microwave over passive microwave is that you can control the illumination rather than depending upon what the surface emits.

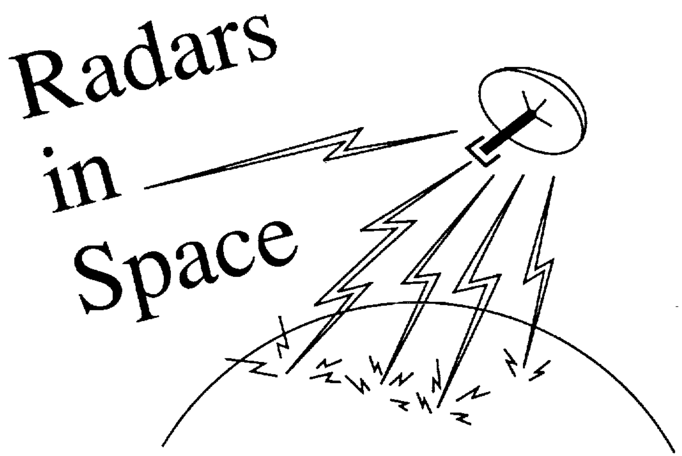
In figure 15, I've listed some trends in space radars. Interferometers allow you to measure the phase difference detected at two different antenna locations that are fairly close together. Knowing the phase difference between the two antennas resolves detail and gives you added opportunity for finer resolution. The term bistatic radar is used when a transmitter is in one location and the receiver is in another. This radar can be two different satellites. We've even had cases in which the transmitter is on a satellite and the receiver is on an airplane that's underflying the satellite. This lets you measure σ^0 as a function of the two different angles, which provides even more information about the scattering surface than you have with just σ^0 of some incidence angle that was the same for both transmit and receive. Anthropologists and Egyptologists can study ancient drainage patterns that are discernible underneath the top layers of sand using active microwave sensors. Inferences are being made concerning ancient civilizations in the Sahara desert. The trend in subsurface sounding of geological formations is to go to even lower frequencies (greater wavelength). According to the formula, the greater the wavelength, of course, the deeper the penetration. Another trend in space radars is combined active/passive methods. This is especially useful in ice classification. NASA Langley Research Center personnel have worked with the Canadian Centre for Remote Sensing to develop in combined active-passive methods to classify ice.

Figure 16 lists technology breakthroughs anticipated in the next few years; these breakthroughs will result in more applications for active microwave. Improved onboard processing of the synthetic aperture radar will be necessary. I mentioned earlier in the definition of σ^0 that the definition for point targets is not really clear and that for calibration purposes it would be useful to have better definitions. In regard to the development of distributive transmitters for large array antennas, we have done quite a bit in distributive receivers and detectors, but we need to do more concerning distributed transmitters. It is also necessary to get more precise control of large antenna surfaces by using methods such as adaptive shaping. The larger the antenna, the more difficult it is to control the surface. Development of "smart" filters is needed to minimize the little smudging and speckling you get in the synthetic aperture radar data. We are extending microwave technology into the millimeter ranges for increased resolution, and taking advantage of certain atmospheric windows.

References

1. Charles Elachi, *Introduction to the Physics and Techniques of Remote Sensing.* Wiley, 1987 (Chapter 6).

2. F. T. Ulaby, R. K. Moore, and A. K. Fung, *Remote Sensing*, Vol. 3, Artech House Inc., 1986.



Backscatter and Cross Section

- *Overview of capabilities of active microwave devices (radars, scatterometers, interferometers, and altimeters operating from Earth orbit).*

- *Basic concepts and definitions commonly used in radar work.*

Figure 1

Outline

General radar parameters

Some basic radar principles
- Surface scattering
- Volume scattering
- Antenna patterns
- Forming a cell on the ground
- Real aperture radar & Doppler
- The Radar Equation
- How to improve ground resolution

Applications
- Synthetic aperture radar
- Radar altimetry
- Geophysically interesting targets

Trends in Space radars
- Anticipated breakthroughs

References

Figure 2

Radars in General

You can control: Frequency
Modulation
Polarization
Incidence angle
PRF, Pulse width

You must record:
Position of radar
Look direction of radar
Range to target
Inc. angle at target

Also, other active microwave devices

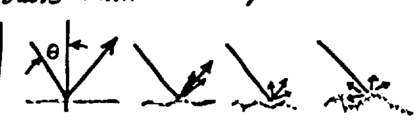
Then you can figure out:
σ° of target for your chosen or observed conditions

And try to relate σ° to geophysically interesting phenomena
(Soil moisture, wind speed, etc.)

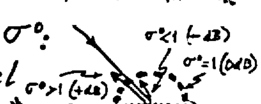
Figure 3

Some Basic Radar Principles

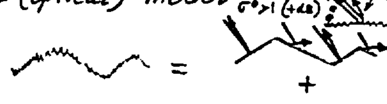
$\boxed{\text{Surface Scattering}}$



σ°:



Specular (optical) model

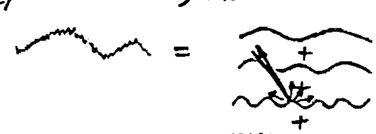


Selection of the scale of $O(\lambda)$

σ° is the Normalized Radar Cross Section, "NRCS," a measure of the backscattering efficiency of the targeted surface.

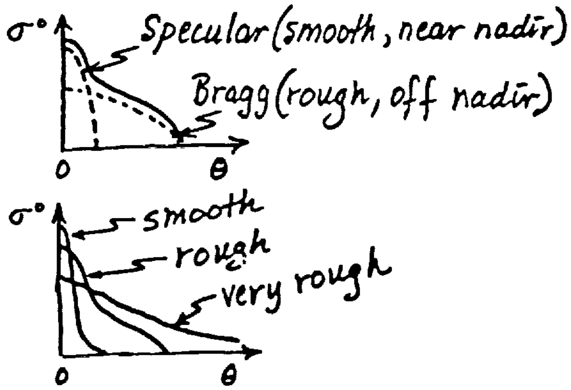
Works best for near-nadir ($\theta < 20^\circ$)
Optical scattering from facets.
$\sigma^\circ \propto$ p.d.f. of surface slope.

Bragg (point scatterer) model



Works best off-nadir. ($\theta > 20^\circ$)
$\sigma^\circ \propto$ Energy spectrum of little bumps.

Figure 4



The rougher the surface,
the less the angular dependence.

In practical radar work, the scattering occurs at many angles (sometimes across a continuum of angles), so a mixture of Specular and Bragg scattering is observed.

Notice the moon's reflection on very calm water. It will appear at just 1 angle. But if the water gets rough, the moon's reflection will be smeared over a wide range of angles.

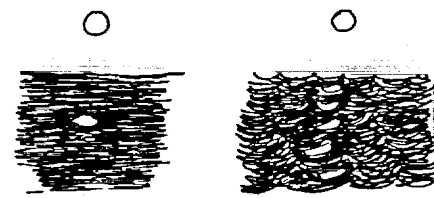
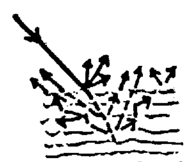


Figure 5

Volume Scattering



lots of internal reflections + the sfc. scatter

Penetration Depth L_p (as in ϵ')

$$L_p = \frac{\lambda}{2\pi\sqrt{\epsilon'}\tan\frac{\epsilon''}{\epsilon'}}$$

at typical microwave λ's,

dry soils	1m
very dry sands	10 m
Polar ice sheets	100m

Can sound through:

snow cover (esp. "dry" snow)
tree canopies

Figure 6

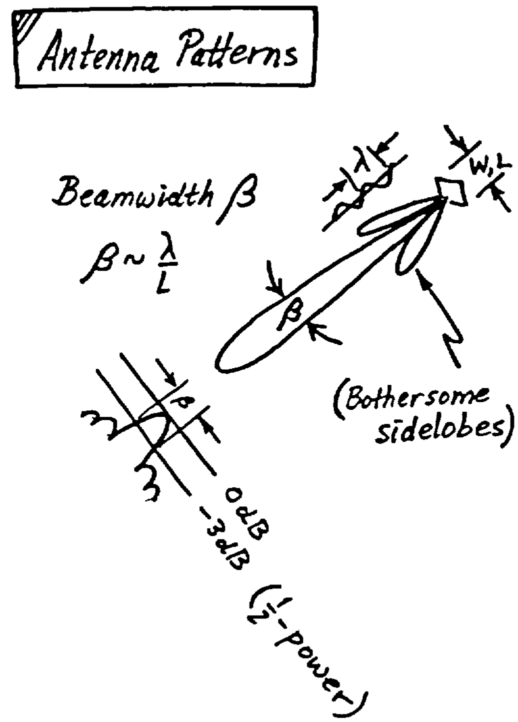
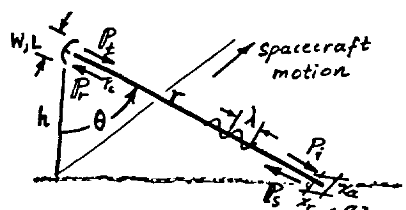


Figure 7

The Radar Equation



$$P_i = \frac{P_t G \cos\theta}{4\pi r^2} \qquad G = \frac{4\pi W L}{\lambda^2}$$

$$P_s = P_i \chi_a \chi_r \sigma^\circ$$

$$P_c = \frac{P_s}{4\pi r^2}$$

$$P_r = W L P_c = \frac{P_t W^2 L c \sigma^\circ \cos^4\theta}{8\pi \lambda h^3 \beta \sin\theta}$$

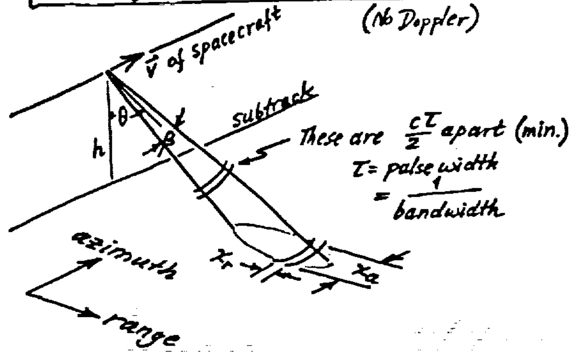
$$SNR = \frac{P_r}{P_N} = \frac{P_r}{kT\, BW}$$

You know P_t, W, L, c, λ, BW, + β
Keep track of h, θ
Measure P_r ⟶ This is the measurement made by a scatterometer.
Solve for σ°
Then model σ° to terrain, water, whatever

Figure 8

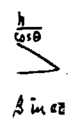
Forming a Resolution Cell on the Ground

(No Doppler)



x_r = resolution in range direction

$$= \frac{c\tau}{2\sin\theta} = \frac{c}{2\,BW\,\sin\theta} \quad \text{typ. } 20\text{ m.}$$



x_a = resolution in azm. direction

$$= \frac{h\lambda}{D\cos\theta} \quad \text{typ. } 1\text{-}2\text{ km } (!)$$

Note x_r indep. of h.

Figure 9

How to improve ground resolution

x_r : $\quad \Delta r \sim \frac{c}{BW} = c\tau$ $\qquad x_r = \frac{c\tau}{2\sin\theta}$

increase BW (decrease τ)
to make Δr smaller

but,
Energy = Peak Pwr $\times$ τ $\qquad$ 10-20m anyway

If Energy gets too low,
can't detect return pulse

Solution: Play tricks by
modulating pulse train
(chirping, phase mod, etc.)

1-2km

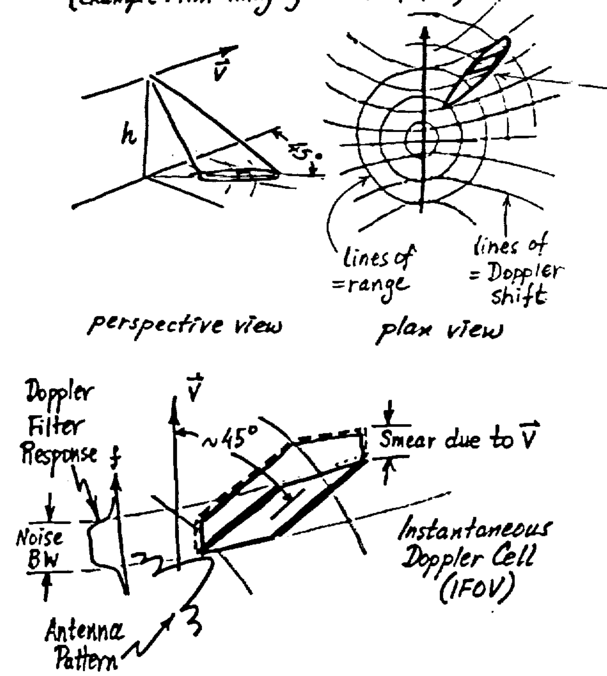
x_a : $\quad \Delta a \sim \frac{h\lambda}{L}$ $\qquad x_a = \frac{h\lambda}{D\cos\theta}$

Do something about L.

Can increase L by going to Synthetic Aperture Radar (SAR), but 1st let's finish up with real aperture radars.

Figure 10

Real Aperture Radar with Doppler Cells
(Example: Non-imaging Scatterometer)

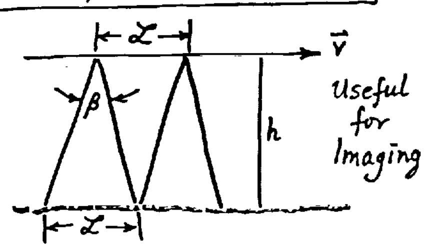


This is one of 4 beams (spaced 90° apart in azimuth) used on SEASAT in 1978. A given patch of water would get "seen" by the 2 beams on that side of the spacecraft. The 2 looks would be 90° apart, allowing calculation of both wind speed and wind direction from the one patch of water.

For SEASAT, the IFOV was about 30 × 50 km, and there were about 14 of them in each beam.

Figure 11

Synthetic Aperture Radar (SAR)



There was also a SAR aboard SEASAT. It imaged both terrestrial and oceanic features, down to about 20m resolution.

Real BeamWidth $\beta = \frac{\lambda}{L}$ Also, $\beta = \frac{\mathcal{L}/2}{h} \Rightarrow \mathcal{L} = \frac{2\lambda h}{L} = 2\beta h$

Synth. BeamWidth $\beta_s = \frac{\lambda}{\mathcal{L}}$ $\mathcal{L}$ = effective ant. length

$\beta_s = \frac{\lambda}{\mathcal{L}} = \frac{L}{2h} \Rightarrow x_a = h\beta_s = \frac{L}{2}$ (Wow!!)

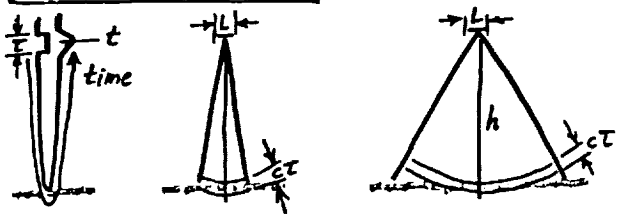
= SAR resolution in azm. direction

Now have $x_a \sim$ a few m, like x_r

SAR Processing: Focused & Unfocused
Focused — phase shift for varying r.
Unfocused — ignore phase shifts $< \frac{\lambda}{4}$

Figure 12

Radar Altimeter



Beam-limited
(for varying terrain)

Pulse limited
(for smooth surface)

$h = \frac{ct}{2}$,
accurate to $\Delta h = \frac{c\tau}{2} = \frac{c}{2BW}$
($\frac{1}{2}$m for SEASAT, 1978)

For an Imaging Altimeter,
Use a narrow beam, and
scan it cross-track (PVO, 1978)

SEASAT also carried a radar altimeter.
Many investigations were conducted in which 2 or more of these active microwave devices were used in combination to extract geophysical parameters that had not been in the original plans for the instruments taken singly.
Also, various combinations of the active devices with the passive, radiometer-type instruments were useful.

Figure 13

Geophysically Interesting Targets for Active Microwave

Wave Structure — water, sand
Geological Faults & Folds
Soil Moisture
Precipitation
Wind Vector over the Ocean
Ice — Extent & Classification
Vegetation
Snow — Extent & Wetness

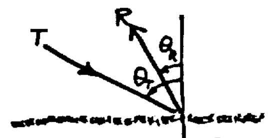
Advantages of Active Microwave
- Cloud penetration
- Day/Night
- All weather (within limits !!)
- Control of illumination

Figure 14

Trends in Space Radars

Interferometers —
resolve position ambiguities w. 2 antennas
1) range from 1 ant. to target
2) Doppler time series
3) Δrange betw the 2 ant's.
4) $\Delta\phi$ at 2 ant's resolves detail

Bistatic radars —



$\sigma^\circ(\theta_T, \theta_R)$ provides new info. about scatt. surface

Subsurface Sounding — $L_p = \frac{\lambda}{2\pi\sqrt{\epsilon'}\tan\frac{\epsilon'}{\epsilon''}}$
Polar Ice
Ancient drainage patterns
Geologic formations
$\Rightarrow$ Go to lower frequencies (greater λ)

Combined Active/Passive
Ice Classification

Figure 15

Anticipated Technology Breakthroughs

Improved on-board processing for SAR's

Better definitions of σ° for point targets (for calibration)

Development of distributed transmitters for large array antennas

Precise control of large antenna surfaces (adaptive shaping)

Development of smart filters to minimize speckling in SAR's

Extension of microwave technology into millimeter ranges, for increased resolution and to take advantage of atmospheric windows.

Figure 16